Ionisation in atmospheres of Brown Dwarfs and extrasolar planets
I The role of electron avalanche

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ABSTRACT

Brown Dwarf and extrasolar planet atmospheres form clouds which strongly influence the local chemistry and physics. These clouds are globally neutral obeying dust-gas charge equilibrium which is, on short time scales, inconsistent with the observation of stochastic ionisation events of the solar system planets. We argue that a significant volume of the clouds in Brown Dwarfs and extrasolar planets is susceptible to local discharge events. These are electron avalanches triggered by charged dust grains. Such intra-cloud discharges occur on time scales shorter than the time needed to neutralise the dust grains by collisional processes. An ensemble of discharges is likely to produce enough free charges to suggest a partial and stochastic coupling of the atmosphere to a large-scale magnetic field.

Subject headings: Brown Dwarfs, planets, atmospheres, clouds, dust, ionisation

1. Introduction

Brown Dwarfs and extrasolar planets have both low luminosity and high surface gravity. Their spectra indicate a complex chemistry due to the low temperatures but high pressures in the atmospheres. This chemical complexity has led to the understanding that condensation processes produce clouds across a large range of effective temperatures (T_{eff} [K]) ranging from late-M dwarfs, the L- and T-dwarfs (Allard et al 2001, Tsuji 2005, Burrows et al. 2006, Stephens et al. 2009) into the planetary regime (Ackerman & Marley 2001, Fortney et al. 2008, Burningham et al. 2008). Irradiation and star-planet interactions have recently added to the richness of the local chemistry (e.g. Fossati et al. 2010, Spiegel et al. 2009) imposing additional non-equilibrium effects (Vidotto et al. 2010 a,b).

This range of spectral types also shows emission at high energies that cannot presently be explained. Quiescent X-ray emission at a constant level of $L_X \approx 10^{-3}\ L_{bol}$ and radio emission at a constant level of $L_{radio} \approx 10^{-7}\ L_{bol}$ are present in solar mass stars and persists in stars of lower masses, all the way down to around M7 (Berger et al 2010). Between M7 and M9 the quiescent level begins to decay, but sporadic, powerful flares are still observed at even later spectral types. A similar slow drop in chromospheric emission is also seen (Reiners and Basri 2002).

In stars like the Sun, this emission is reasonably well understood. These stars generate a magnetic field within their convective interiors. This field rises buoyantly through the interior, to emerge at the stellar surface and extend into the outer atmosphere. The convective motions generate waves along these field lines that transmit some fraction of the convective energy into the outer atmosphere where it is released in reconnection events. The largest of these are observed as X-ray[1] and radio flares, while the smallest serve to provide the quiescent level of X-ray emission required to power the corona (Parker 1988). This process, however, relies on a coupling between the convective fluid motions and the magnetic field. Without this coupling, energy cannot be stored in the magnetic field and hence cannot be released in the outer atmosphere to generate coronal X-ray emission. As demonstrated by Mohanty et al (2002), however, stellar objects between M5 and L6 are too cool for this coupling to be effective. Thermal ionisation processes are simply not sufficient to provide a high enough ionisation fraction. If these non-binary low mass objects are so cool, then, how do we explain the observed X-ray emission? The presence of this emission indicates an ionised atmosphere, but the cause of this ionisation is unknown.

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[1]The X-ray luminosity results from thermal gyrosynchrotron radiation resulting from thermally produced electrons only.

The key to this puzzle may lie in the dust clouds that begin to form in low mass stars at around the same effective temperature range where thermal ionisation processes die away. Within the solar system, cloud-covered planets are observed to produce various kinds of discharge events (e.g. Yair 2008). On Earth, dust storms and volcanoes are examples for strong intra-cloud discharging of dusty gases. We argue in this paper that such discharge events are to be expected in the dusty gases of extrasolar atmospheres, in analogy to their solar system counterparts. If they could raise the ionisation fraction by a sufficient amount, over a large enough volume, then they may be able to explain the presence of sustained quiescent X-ray emission in objects as cool as M9 and the presence of large flares in even lower mass objects.

There is, however, an immediate problem with this suggestion, which is that classical charge equilibrium arguments point to a rapid neutralisation of dust particles. This would imply that these cool, dusty atmospheres are neutral, at least on long time scales. Observations of solar system planets and laboratory discharge events, however, suggest that on *short* timescales, discharge events should be expected. We propose that some rapid process, such as the electron avalanche believed to act in lightning bolts, may operate. Assuming that dust grains can be charged for long enough for avalanches to occur, they may be capable of providing local and intermittent ionisation. Depending on the volume of the atmosphere that is susceptible to this process, and the frequency with which it occurs, this may be capable of explaining a low level of magnetic field coupling and hence quiescent X-ray emission, or only intermittent coupling, leading to occasional flaring.

In Sect 2, we first briefly summarise cloud properties of Brown Dwarfs and extrasolar planets and we investigate the geometrical extension of clouds depending on the fundamental parameters T_{eff} and $\log(g)$. By assuming that the dust grains, which compose the clouds, are charged, we discuss their effect on the local charge balance in Sect. 3. In Sect. 4, we demonstrate that dust-initiated electron avalanches are a strong candidate to temporally increase the local degree of gas phase ionisation in the atmospheres of Brown Dwarfs and extrasolar planets.

2. Dust in Brown Dwarf and exoplanetary atmospheres

We analyse results from the dust cloud model developed by Woitke & Helling (2003, 2004), Helling & Woitke (2006), and Helling, Woitke & Thi (2008) describing consistently the formation of a stationary cloud by homogeneous nucleation and dirty growth/ evaporation, including gravitational settling, element depletion, and convective element replenishment. In the following, we utilise DRIFT-PHOENIX atmosphere models (Dehn 2007, Helling et al.

2008a,b; Witte, Helling & Hauschildt 2009) in which our detailed kinetic model of dust cloud formation is coupled with a radiative transfer code (Hauschildt & Baron 1999, Baron et al. 2003). This allows for a consistent solution of the model atmosphere problem and the dust cloud model from which we derive the geometrical extension of the cloud. Based on DRIFT-PHOENIX model atmospheres, we have shown that clouds form in atmospheres of Brown Dwarfs and extrasolar planets, and that they are composed of chemically heterogeneous grains of various sizes. The local grain size distribution is dominated by small grains at the cloud top and by large grains at the cloud base. These dust grains gravitationally settle and change their chemical composition and their sizes during this journey through the atmospheric temperature gradient until they evaporate. The cloud's material composition, however, is similar amongst the Brown Dwarfs and giant gas planets (Helling, Woitke & Thi 2008) except if the element abundances are very low ($[M/H]< -4.0$; Witte, Helling & Hauschildt 2009). The geometrical cloud extension can change considerably with $\log(g)$.

The geometrical extension of the cloud is determined by the maximum distance over which grains can fall before they evaporate. The cloud extension[2] is taken as the geometrical distance between the first nucleation maximum (cloud top) and the point at which the dust has evaporated at high temperatures (cloud base), hence $\Delta H_{\mathrm{cloud}} = (r_{\mathrm{top}} - r_{\mathrm{base}}) \cdot R_*$ where fractional distances r are scaled to the radius R_*. Figure 1 (top) shows that the dependence of the cloud extension on the Brown Dwarf's T_{eff} is comparably weak with a cloud extension of $H_{\mathrm{cloud}} \approx 0.00036 \ldots 0.00041 R_*$. As an example, a Jupiter-sized Brown Dwarf ($R_* = R_{\mathrm{J}} = 7.1492 \cdot 10^9$cm; equatorial Jupiter radius) with a surface gravity of $\log(g)$=5.0 would form clouds that spanned 27.5km i.e. $0.000385 R_*$ (Fig. 1, top). Measuring cloud extension from observations is, however, not straightforward as observations only access the (frequency-dependent) optically thin part of the cloud while the geometrical extension of the cloud layer is often much larger (e.g., Banfield et al. 1998, Matcheva et al. 2005 for Jovian clouds, Pont et al 2008 and Sing et al. 2009 for extra-solar clouds).

The extension of the cloud changes much more significantly, however, with $\log(g)$ (Fig. 1, bottom). It increases considerably for young Brown Dwarfs and gas giant planets as they have a much lower surface gravity of $\log(g) \approx 2.5 - 4.0$ compared to old Brown Dwarfs with $\log(g) > 4.0$. This reflects the increasing pressure scale height with decreasing gravity as $\Delta H_{\mathrm{p}} \sim 1/g$. The cloud extension increases from $\Delta H_{\mathrm{cloud}} = 0.004 \ldots 0.005 R_*$ for $\log(g)$=4.0 to $\Delta H_{\mathrm{cloud}} = 0.03 \ldots 0.04 R_*$ for $\log(g)$=3.0 by almost a factor 10 (Fig. 1). Table 1 shows

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[2] This definition is different to Woitke & Helling (2004). The geometrical thickness of the cloud layer was defined in Woitke & Helling (2004) as the degree of condensation of Ti $f_{\mathrm{cond}}^{\mathrm{Ti}} = \epsilon_{\mathrm{Ti}}^{\mathrm{dust}}/\epsilon_{\mathrm{Ti}}^0 > 1/e$ having decreased to $1/e$ at the cloud deck and the cloud base. ϵ^{dust} is the element abundance contained in the solid phase and ϵ_{Ti}^0 the undepleted element abundance.

examples for Brown Dwarfs and WASP planets by assuming that $\Delta H_{\mathrm{cloud}}$ varies only slowly with $\mathrm{T}_{\mathrm{eff}}$. Depending on the object's radius and surface gravity, the cloud extension varies between some 10km and 5000km.

3. Charge balance in dusty atmospheres

We therefore expect that Brown Dwarfs and extrasolar planets will form dust clouds whose geometrical extent depends mainly on the surface gravity. Although the presence of these dust clouds undoubtedly influences the local chemistry, it remains an open question whether they can significantly influence the large-scale dynamics. The observation of X-ray flares and coherent radio emission from Brown Dwarfs (Berger et al. 2010) suggests that they must possess a magnetic field. The presence of a global magnetic field opens up the possibility of coupling between this field and the gas in which it is embedded. In this case, by analogy with the Sun and solar-type stars, we would expect that the magnetic field may become twisted and tangled by the convective motions. This process stores magnetic energy throughout the field and it is the release of this energy by many reconnection events that is believed to power the persistent X-ray emission from the coronae of solar-like stars. If, as on the Sun, Brown Dwarf flares are magnetically-powered, then there must have been at least a short-term, coupling between the magnetic field and the plasma.

The level of this field coupling is typically measured by the value of the magnetic Reynolds number R_{m} which is the ratio of the advective and diffusive contributions to the temporal evolution of the magnetic field. A magnetic field may be considered to be effectively coupled to the plasma if diffusion is negligible compared to advection and hence $R_{\mathrm{m}} > 1$. This requires, however, that there is a significant level of ionisation of the plasma, since the magnetic Reynolds number is proportional to the atmospheric ionisation fraction $f_{\mathrm{e}} = p_{\mathrm{e}}^{\mathrm{tot}}/p_{\mathrm{gas}}$, such that

$$R_{\mathrm{m}} = u\,l\,\eta_{\mathrm{d}}^{-1} \tag{1}$$

$$= u\,l \cdot \frac{4\pi\,q^2}{m_{\mathrm{e}}c^2}\frac{1}{\langle\sigma v\rangle_{\mathrm{en}}} \cdot f_{\mathrm{e}}, \tag{2}$$

where η_{d} is the magnetic diffusivity, q is the electric charge, c is the speed of light, m_{e} is the mass of the free electron, and $\langle\sigma v\rangle_{\mathrm{en}} \approx 10^{-9}$ cm^{3}s^{-1} is the collisional cross section (velocity averaged momentum transfer cross section; Pinto & Galli 2008). We choose $u = 10^4$ cm/s as representative, large scale velocity value (Fig. 9 in Freytag et al. 2010), and $l = 10^5$cm.

The magnetic Reynolds number and hence the degree of atmospheric coupling will therefore vary with depth in the atmosphere as the ionisation fraction varies. Figure 2

demonstrates this variation using the local gas pressure as a measure of atmospheric depth, while Figure 3 describes its variation with the cloud's radial fraction [r/R$_*$]. Figure 2 contains results of several different atmospheric codes. The DRIFT-PHOENIX results are compared to results for the DUSTY-PHOENIX (green dashed line, Fig. 2) and the COND-PHOENIX (brown dashed lines, Fig. 2) model atmospheres[3]. DUSTY-PHOENIX produces a considerably higher R_{m} due to thermal gas ionisation owing to an overall hotter temperature in the atmosphere compared to COND-PHOENIX and DRIFT-PHOENIX[4].

Only the very inner parts of the atmosphere reach $R_{\mathrm{m}} > 1$ by thermal gas ionisation in the DUSTY- and DRIFT-PHOENIX model atmospheres. Thermal gas ionisation is, hence, not sufficient to couple the gas inside and above the dust cloud to the magnetic field as already shown by Gelino et al. (2002) and Mohanty et al. (2002). A significant increase in the electron number density would be required to ensure that $R_{\mathrm{m}} > 1$. In order to illustrate this point, we show in Fig. 2 that an increase of the electron number density by a factor 10^6 per cloud altitude would be needed to ensure $R_{\mathrm{m}} > 1$ (long dashed red line, Fig. 2). This translates into $> 50\%$ of the cloud (long dashed red line in Fig. 3) being coupled to any magnetic field present. This would be the inner ~ 13km of a cloud of a Jupiter-sized Brown Dwarf (Sect. 2). Note that the atmospheric volume concerned increases with decreasing surface gravity of the object, and hence, for young Brown Dwarfs or giant gas planets (Sect. 2).

It is clear, therefore, that in order to maintain a state whereby most of the cloud is ionised sufficiently to ensure an effective coupling to any magnetic field present, we require a significant and sustained enhancement of the electron number density. The magnitude of this enhancement can be illustrated quite simply by considering charge balance in the cloud. The electron density, n_{e}, changes due to electron production processes ($I = I_{\mathrm{gas}} + I_{\mathrm{dust}}$) and electron recombination processes ($R = R_{\mathrm{gas}} + R_{\mathrm{dust}}$), such that, in equilibrium,

$$\frac{dn_{\mathrm{e}}}{dt} = I_{\mathrm{gas}} + I_{\mathrm{dust}} - R_{\mathrm{gas}} - R_{\mathrm{dust}} = 0. \tag{3}$$

We neglect the thermal gas-phase processes, I_{gas} and R_{gas}, as we (also Gelino et al. 2002, Mohanty et al. 2002) have demonstrated that thermal ionisation of the gas phase is negligible in Brown Dwarf atmospheres. If the electron production and electron neutralisation are due

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[3]DUSTY-PHOENIX and COND-PHOENIX are older versions of the PHOENIX mode atmosphere results where the existence of dust was assumed rather than its formation calculated.

[4]The different definition for the magnetic diffusivity used by Gelino et al (2002) results in smaller magnetic Reynolds numbers (black lines).

to collisional processes with the dust grains only, then

$$I_{\text{dust}} \quad \sim \quad N n_{\text{d}}^2 \pi a^2 v_{\text{rel}}, \tag{4}$$

$$R_{\text{dust}} \quad \sim \quad n_{\text{e}} n_{\text{d}} \pi a^2 c_{\text{e}}, \tag{5}$$

with n_{d} the dust number density, N the number of charges produced by a collisions, a the dust grain radius, v_{rel} a relative velocity, and c_{e} the electron thermal velocity. Thus we simply have

$$\frac{I_{\text{dust}}}{R_{\text{dust}}} \sim N \frac{n_{\text{d}}}{n_{\text{e}}} \frac{v_{\text{rel}}}{c_{\text{e}}}. \tag{6}$$

The presence of dust can only significantly increase the electron density if $I_{\text{dust}} \gg R_{\text{dust}}$ and, hence $N n_{\text{d}} \gg n_{\text{e}}$. Since the number density of dust grains is so much less than that of electrons, we require that the number of charges N produced by collisions must increase dramatically. We estimate that $I_{\text{dust}}/R_{\text{dust}} \sim 7 \cdot 10^{-13} N$, hence we require $N > 1.4 \cdot 10^{12}$ in the low-pressure part at $p_{\text{gas}} \sim 10^{-5}$bar of the cloud[5]. Conditions would be more favourable at higher pressures as fewer free charges would be needed: At a pressure of 10^{-2}bar, $I_{\text{dust}}/R_{\text{dust}} \sim 8.5 \cdot 10^{-11} N$, and hence only $N > 1.2 \cdot 10^{10}$ is required[6]. These numbers are, however, sufficiently large that it is unlikely that the simple collisional processes we have considered will be sufficient to produce an equilibrium state with $R_{\text{m}} > 1$. We therefore expect that even in the presence of dust clouds, the atmospheres of Brown Dwarfs should be globally neutral. This does not, however, preclude short-term departures from equilibrium which might (as in the solar system) lead to transient ionisation events.

Concluding this section, we have demonstrated that a considerable number of additional charges is needed to allow $R_{\text{m}} > 1$, or equivalently, to provide a minimum degree of ionisation of $f_{\text{e}} > 10^{-7}$. These charges need to be produced (or separated) on a time scale shorter than a classical collisional recombination time scale of grains in order to keep the atmosphere globally neutral over a long time scale.

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[5]We have adopted values for the low-pressure part of a cloud at $p_{\text{gas}} \sim 10^{-5}$bar where $T \sim 1000$K, $n_{\text{d}} \sim 10^{-10}$cm^{-3} (Helling et al. 2008b), $v_{\text{rel}}^{\text{drift}} \sim 10^4$ cm s^{-1} (Witte, Helling, Hauschildt 2009), $n_{\text{e}} \sim 0.076$ cm^{-3} for $p_{\text{e}} \sim 10^{-14}$ dyn cm^{-2}. The electron thermal velocity is $c_{\text{e}} = \sqrt{2\,kT/m_{\text{e}}} \sim 1.7 \cdot 10^7$ cm s^{-1}.

[6]We have adopted values for a part of the cloud with a higher pressure of $p_{\text{gas}} \sim 10^{-2}$ bar where $T \sim 1150$K, $n_{\text{d}} \sim 10$cm^{-3} (Helling et al. 2008b), $v_{\text{rel}}^{\text{drift}} \sim 10^2$ cm s^{-1} (Witte, Helling, Hauschildt 2009), $n_{\text{e}} \sim 6.3\,10^5$ cm^{-3} for $p_{\text{e}} \sim 10^{-8}$ dyn cm^{-2}. The electron thermal velocity is $c_{\text{e}} = \sqrt{2\,kT/m_{\text{e}}} \sim 1.9 \cdot 10^7$ cm s^{-1}.

4. Electron avalanche in clouds

We have argued that the consideration of thermal and dust-collisional processes alone suggests a globally neutral atmosphere, but that processes acting on shorter time scales can cause a violation of strict charge equilibrium locally. This would be consistent with intermittent X-ray flares on Brown Dwarfs, where an rapid release of energy produces intense X-ray emission for a short time, followed by long periods of quiescence. We suggest electron avalanche initiated by charged dust grains as one candidate for the fast production of large amounts of free charges, and hence as source for a locally increased degree of gas-ionisation in the atmospheres of Brown Dwarfs and extrasolar planets.

We assume that dust grains are charged, as discharge events are observable in a variety of environments (terrestrial thunder clouds, dust devils, volcano plumes) and are expected to occur in others (protoplanetary disks, Desch & Cuzzi 2000). These dust grains form and have relative velocities e.g. by gravitationally settling and turbulence which determines the cloud's geometrical extension in an atmosphere (Woitke & Helling 2003; Helling et al. 2006).

Experiments have shown that a 100μm particle can carry 10^5 elementary charges (Sickafoose et al 2000). If we consider grains that are 3 orders of magnitude smaller, their charge load will be smaller by about the same order of magnitude. Helling, Woitke & Thi (2008) have shown that the cloud's grain size distribution per altitude can be very broad in particular in low-gravity objects (log(g)=3.0) containing of order 10^4 particles as large as 10μm. If these large particles would only release 1/100 of their accumulate 10^4 charges into the gas phase before electron recombination, $> 50\%$ of the cloud would achieve $R_{\mathrm{m}} > 1$ (see Fig. 3). These charges may, however, neutralise by collisional recombination unless an avalanche instability like for instance in streamers can develop on a shorter timescale (see Sect. 4.1).

If enough charges remain on the grain surface (or none are released into the gas phase), and the grains move with a relative velocity, a strong electric field can be established that initiates a small-scale discharge between the grains. A current forms that tries to establish charge balance. Free thermal electrons gain enough energy when moving through the grain's small-scale electric field to be able to ionise the gas between the grains. Eventually the field disappears as the grains move further apart. What remains is a partly ionised ambient atmosphere while the charged grains escape due to gravitational settling. We can estimate the electric field developed by considering a spherical grain of mean size $a = 0.5\mu$m carrying $q = 3 \cdot 10^3\, e$ charges (Desch & Cuzzi 2000). This gives

$$E = \frac{q}{4\pi\varepsilon_0 a^2} = 20\mathrm{MVm}^{-1} \tag{7}$$

where ε_0 is the electrostatic field constant, and e is the elementary charge. Dowds, Barrett & Diver (2003) demonstrate the effectiveness of a succession of these avalanches (known as a

streamer in ionising the nitrogen gas between two capacitor plates for a field strength of only $5 \mathrm{MV\,m^{-1}}$. Li et al. (2007) and Li, Ebert & Brok (2008) support this finding for an electric field strength of $10 \mathrm{MV\,m^{-1}}$ from their study based on different numerical methods. Hence, the field strength between charged grains is sufficient to produce streamers that enhance the local degree of gas ionisation inside the dust cloud. The electric field will be stronger if the grain's shape depart from spherical symmetry (Stark, Potts & Diver 2006).

The streamers that form are a growing ionisation front that propagates into non-ionised matter. They are present in lightning ladders and they can emerge from ionisation avalanches in weakly ionized plasmas in free space. Such field breakdowns are stochastic and non-linear processes that produce an exponentially increasing number of charges. Streamers are self-sustaining (hence an instability), and each streamer is ignited by the large number ($\sim 10^6$) of free charges produced by the avalanche of the accelerated electron from one gas-phase electron-ion pair. Between 10^{13} and 10^{14} cm^{-3} free charges form during the consecutive avalanches in the streamer (Dowds, Barrett & Diver 2003, Li et al. 2007). One streamer alone is therefore capable of satisfying $I_{\mathrm{dust}} \gg R_{\mathrm{dust}}$ locally, and hence causing departure from local charge equilibrium.

Such local ionisation events are only likely to be capable of explaining the observations of Brown Dwarf flares and radio emission if they occur over a sufficiently large volume of the atmosphere. The cloud grains, however, are confined to a certain volume of the atmosphere by thermodynamic constrains. This volume increases with decreasing surface gravity as we have shown in Sect. 2. The cloud height would be the maximum size that a streamer leading to a lightning bolt could achieve in the case of intra-cloud lightning. In this volume, the simultaneous occurrence of discharge in streamers will occur, and the gas in the cloud could then locally couple to the magnetic field for a short time appearing as e.g. stochastic flares. Over a recombination time, we expect that these excess charges will recombine onto dust grains.

4.1. Neutralisation versus avalanche time scales

We have argued that dust grains populate Brown Dwarf and extrasolar planet atmosphere over a extension that varies mainly with gravity. We have further argued that non-linear processes are needed to produce discharge processes such as those in solar system planets, and we have suggested exponential electron avalanche as an attractive possibility. It remains to be shown if the grains could be neutralised by gas-dust collisions quickly enough to prohibit the built-up of the streamer-avalanche mechanism that leads to the appearance of lightning bolts.

Dowds, Barrett & Diver (2003) carried out numerical experiments where the electron avalanche process and the development of streamers were studied between two 0.1cm-size capacitor plates with a plate distance of 5μm. The capacitor was filled with nitrogen gas of a typical terrestrial atmospheric pressure of 1bar. They show that a streamer is fully developed after about $\tau_{\rm str}$ =0.2ns (= $2 \cdot 10^{-10}$s; green symbol, Fig. 4), a time scale confirmed by comparable works of Li, Ebert & Brok (2008) and by 3D simulations of Li, Ebert & Hundsdorfer (2009). Following Ebert et al. (2010), we scale $\tau_{\rm str}$ with the local gas pressure as $\tau_{\rm str} \sim 1/p_{\rm gas}$ (solid black line, Fig. 4, [7]).

To estimate the grain charge neutralisation time scale we adopt the neutralisation rate given by Desch & Cuzzi (2000; Eq. 24) which assumes that electrons can freely impinge on the positively charged grain's surface if the Coulomb energy of the grain is larger than the thermal kinetic energy of the electrons. This time scale provides an estimate for efficient neutralisation as electrons have a higher mobility than the much heavier ions. From their formula, one derives the neutralisation time scale for a grain of size a (Eq. 25 in Desch & Cuzzi 2000) in cgs units[8] applying the mean grain size, $<a>$, from our DRIFT-PHOENIX model

$$\tau_{\rm recom}^{\rm cgs} = \frac{1}{q^2} \frac{kT}{n_{\rm e} c_{\rm e} \pi <a>}, \tag{10}$$

where $n_{\rm e}$ is the gas-phase electron density, $c_{\rm e} = \sqrt{2\,k\,T/m_{\rm e}}$ is the electron thermal velocity and $m_{\rm e}$ is the electron mass. We show two limiting cases for the grain charge q according to Fortov et al. (2001) where small grains carry of the order of $q = 10\,e$ (each uper line) and large grains $q = 10^2\,e$ (each lower line). The elementary charge is in units of $e = 4.803 \cdot 10^{-10}$statC. We also include the recombination time-scales for a hotter ($T_{\rm eff}$ = 2000K, log(g)=5.0; green long dashed) and a lower-gravity atmosphere model ($T_{\rm eff}$ = 1600K, log(g)=3.0; red short dashed) for comparison. The time scale for dust grain neutralisation by impinging electrons is

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[7]The time scale to establish a streamer can also be defined as

$$\tau_{\rm str} = \frac{N(x(t))}{\frac{dN(x(t))}{dt}}, \tag{8}$$

with $N(x(t)) = N_0 \exp(\frac{x(t)}{\lambda_{\rm e}})$ the exponential growth of charges in a streamer (e.g. Braithwaite 2000). With N_0 the initial values of number of charges dropping out of Eq. 8, by assuming a stationary electron velocity ($dx(t)/dt = const$) through the capacitor, and with the electron's mean free path $\lambda_{\rm e} \sim 1/p_{\rm gas}$ follows that $\tau_{\rm str} \sim 1/p_{\rm gas}$.

[8]The neutralisation time scale is in SI units ($e = 1.602 \cdot 10^{-19}$C),

$$\tau_{\rm recom}^{\rm SI} = \frac{4\pi\epsilon_0}{q^2} \frac{kT}{n_{\rm e} c_{\rm e} \pi <a>}. \tag{9}$$

longer than the time needed to establish a streamer (solid black line) throughout a significant fraction of the cloud in all the model atmospheres considered (Fig. 4). Only the largest particles at the cloud base would neutralise too quickly for the streamer mechanisms to kick in efficiently if the neutralisation process proceeds without collisions as assumed in Eq. 10. We note that this is also the part of the cloud where the largest particles accumulate and quickly evaporate inside a narrow cloud layer. These grains are almost pure metal as they are made of $Fe[s]$ with small inclusions of $TiO_2[s]$ and $Al_2O_3[s]$ followed by a thin cloud region with almost homogeneous $Al_2O_3[s]$ grains ([s] – solid).

5. Conclusions

Brown Dwarf and extrasolar planet atmospheres form clouds which strongly influence the local chemistry and physics. These clouds need to form from the gas-phase as Brown Dwarfs and most of the planets do not have a crust from which seed particles can be swept up. These clouds are globally neutral obeying dust-gas charge equilibrium. On short time scales, however, stochastic ionisation events may occur as observed in the solar system planets. We have argued that a large part of the clouds in Brown Dwarfs and extrasolar planets is susceptible to local discharge events which are triggered by charged dust grains. Such discharges occur on time scales shorter than the time required to neutralise the dust grains, and their superposition might produce enough free charges to suggest a partial and stochastic coupling of the atmosphere to a large-scale magnetic field. Discharge processes in Brown Dwarf and exoplanetary atmospheres can not connect to a crust as on terrestrial planets, hence, they will experience intra-cloud discharges comparable to volcano plumes and dust devils.

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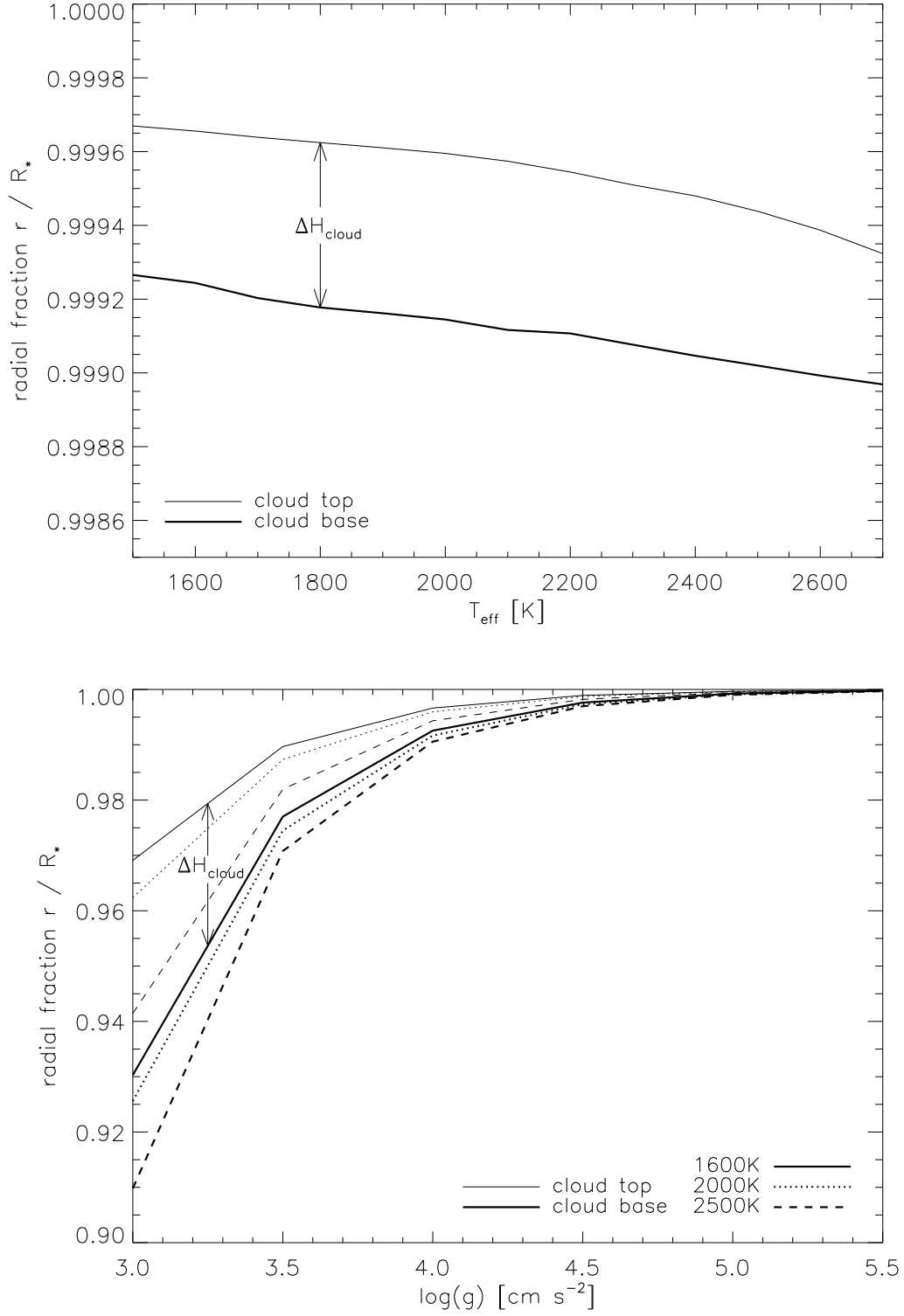Fig. 1.— Cloud extension $\Delta H_{\mathrm{cloud}} = (r_{\mathrm{top}} - r_{\mathrm{base}}) \cdot R_*$ as function of $\mathrm{T_{eff}}$ (top, $\log(g)$=5.0) and $\log(g)$ (bottom) from DRIFT-PHOENIX model atmospheres. The cloud's top (@r_{top} [$\mathrm{R_*}$], thin lines) is defined at the fist nucleation maximum, the cloud base (@r_{base} [$\mathrm{R_*}$], thick lines) is defined at the location where all dust is evaporated (Fig. 2 in Witte, Helling & Hauschildt 2009).
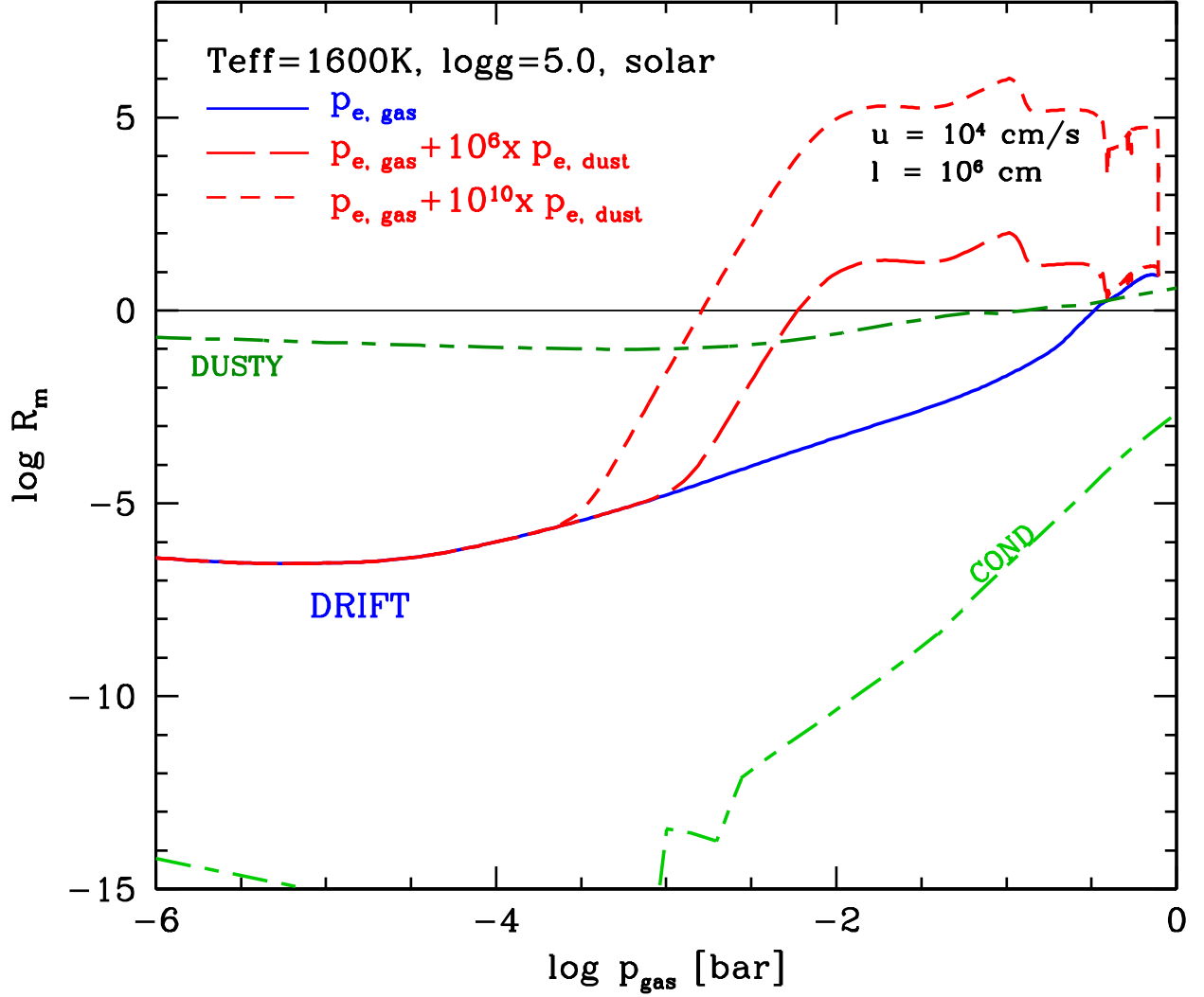
Fig. 2.— Magnetic Reynolds number, $R_m = u\,l\,\eta_d^{-1}$, for a DRIFT-PHOENIX model atmosphere (blue) and a comparison with DUSTY-PHOENIX (dark green) and COND-PHOENIX (light green) results for thermal gas ionisation only. Magnetic coupling of the gas to a magnetic field is expected if $R_m > 1$, hence above the black horizontal $R_m = 1$ line. Overplotted are the the cases with a charge production that has been artificially increased by a factor of 10^6 (long dashed line) and 10^{10} (short dashed line) inside the cloud. This demonstrates that magnetic coupling can be expected in limited parts of the dusty atmosphere if such a high number of charges can be produced.
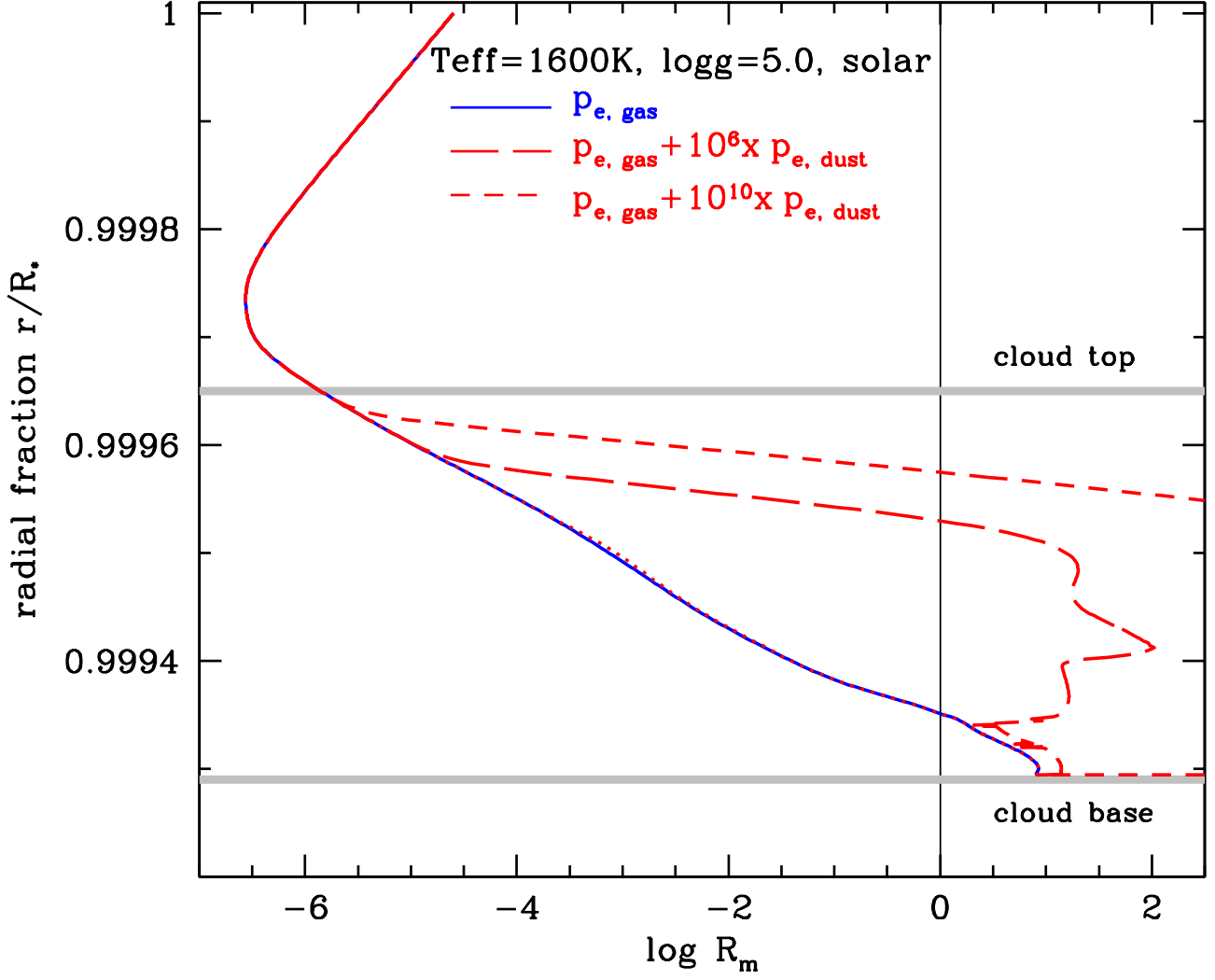
Fig. 3.— Magnetic Reynolds number, $R_{\mathrm{m}} = u\,l\,\eta_{\mathrm{d}}^{-1}$ in relation to the cloud height for the DRIFT-PHOENIX model atmosphere only. 'Cloud top' and 'cloud base' are defined as in Fig. 1.
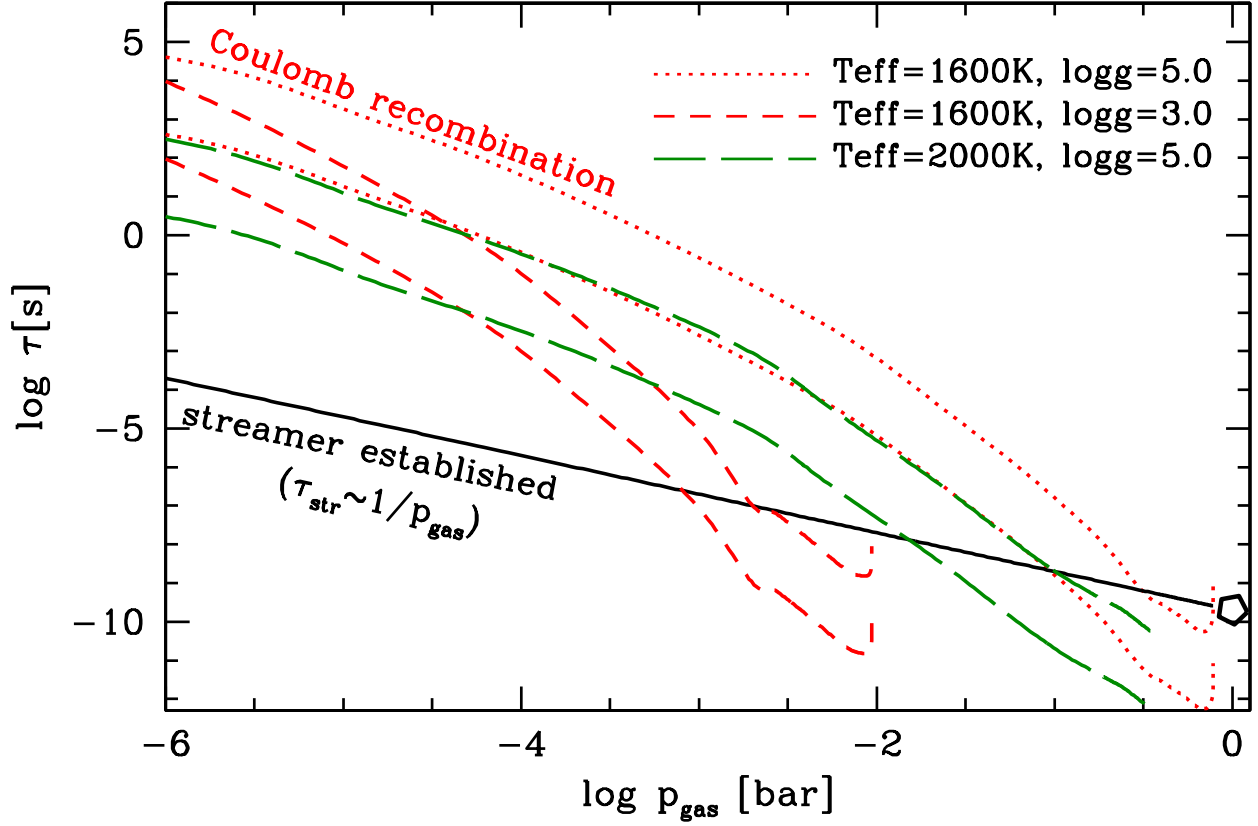
Fig. 4.— The time scale of grain neutralisation by freely impinging electrons $\tau_{\mathrm{recom}}^{\mathrm{cgs}}$ (red and green dashed and dotted lines) compared to the time required to establish a streamer τ_{str} (black solid line). The neutralisation time scale τ_{str} is shown for three different DRIFT-PHOENIX atmosphere models (hot/cold and high/low log(g)) which are each evaluated for two cases: charge load of small grains ($q = 10\,e$, upper line) and larger grains ($q = 10^2\,e$, lower line). The black symbol is the numerical data from Dowds, Barrett & Diver (2003) extrapolated such that $\tau_{\mathrm{str}} \sim 1/p_{\mathrm{gas}}$ (Eq. 8).

Table 1: Cloud extension, $\Delta H_{\mathrm{cloud}}$, for Brown Dwarfs and WASP-like giant gas planets ($R_{\mathrm{J}} = 7.1492 \cdot 10^9$cm – equatorial Jupiter radius; $R_{\odot} = 6.9598 \cdot 10^{10}$cm – solar radius) as derived from the DRIFT-PHOENIX atmosphere simulations results in Figs. 1. All T_{eff} for the WASP planets are taken as A=0 (A - albedo; see references in table).

WASP 12b		**WASP 15b**	
(Hebb et al. 2009)		(West et al. 2009)	
T_{eff}=2516K **cloud extension:**		T_{eff}= 1652K **cloud extension:**	
$\log(g) = 2.9$	0.03 $R_* =$	$\log(g) = 2.8$	0.04 $R_* =$
$R_* = 1.79$ R_{J}	**3820km**	$R_* = 1.43$ R_{J}	**3830km**
WASP 10b		**WASP 14b**	
(Christian et al. 2009)		(Joshi et al. 2009))	
T_{eff}=1119K **cloud extension:**		T_{eff}= 1866K **cloud extension:**	
$\log(g) = 3.6$	0.011 $R_* =$	$\log(g) = 4.0$	0.005 $R_* =$
$R_* = 1.28 R_{\mathrm{J}}$	**1000km**	$R_* = 1.28 R_{\mathrm{J}}$	**410km**
binary system 2MASS J05352184-0546085			
(Stassun et al. 2007)			
$T_{\mathrm{eff},1} \sim 2700$K**cloud extension:**		$T_{\mathrm{eff},2} \sim 2800$K**cloud extension:**	
$\log(g)_1 = 3.5$	0.012 $R_* =$	$\log(g)_2 = 3.6$	0.011 $R_* =$
$R_{*,1} = 0.67 R_{\odot}$	**5620km**	$R_{*,2} = 0.48 R_{\odot}$	**3710km**